High-Resolution Measurement-Based
Phase-Resolved Prediction of Ocean Wavefields

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LONG-TERM GOAL

The primary focus of this research is to develop a phase-resolved capability for intermediate scale, O(10)km, wave environment prediction by integrating whole-field and multiple-point direct measurements of the wave and atmospheric environment with nonlinear simulation-based reconstruction of the wavefield. Given remote and direct physical measurements of a realistic ocean wavefield, we aim to obtain a high-resolution description of the wavefield with direct wave computations including realistic environmental effects such as wind forcing and wave breaking dissipation. We will inform and guide the measurements necessary for achieving this reconstruction and address the validity, accuracy and limitations of such wavefield reconstructions.

OBJECTIVES

The scientific and technical objectives of this research are:

- development of wave reconstruction and prediction capability

- understanding reliability/accuracy/robustness and limitations of direct wave measurement based, phase-resolved modeling

- direct quantitative comparisons between wave model prediction and field measurements

APPROACH

For wave reconstruction and prediction, we use a high-order spectral (HOS) method to simulate full nonlinear wave interactions including wind forcing and wave breaking modeling. The simulation uses as input hybrid (radar and probe) measurement data that may be noisy, uncertain/incomplete. Physics-based wind-forcing models will be developed based on a coupling of large-eddy simulation of winds (LES) and large-wave simulation (LWS) of dynamic waves and wave groups with nonlinear wavefield evolution computations. We will adopt an adaptive simulation methodology to model local steep wave dynamics and wave breaking, and incorporate wave breaking dissipation into deterministic wave reconstruction and forecast. The simulation will be compared to and validated with field measurements directly.   Finally, a multiscale approach will be employed to incorporate data from meso-scale meteorological models, ABL simulations, fine-scale CFD, and field measurements at various scales to provide spatial-temporal input for wavefield simulation.

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In order to understand the reliability/accuracy/robustness and limitations of direct wave measurement based phase-resolved modeling, we will first use the existing wave reconstruction/prediction capability and available radar data to test out the accuracy of radar measurements of ocean surface waves and to answer the fundamental question of how well marine radar systems can represent the ocean surface wave field. Based on spatial/temporal predictions of simulated wavefields in relation to hybrid radar and probe wave data, we will then develop a theoretical framework for guiding deployment of wave sensing systems and data utilization and interpretation. We will use existing radar wave measurements to test and to validate the accuracy of the reconstruction and forecasting model, to investigate the uniqueness and robustness of the reconstruction scheme, and to develop a framework to properly retrieve wave information in shadows and gaps of radar-sensed wavefield data. Finally, we will characterize and quantify the effects of noise and uncertainty in sensing data on phase-resolved wavefield prediction, and develop efficacious approaches to minimize these effects in the prediction.

Direct quantitative comparisons between wave model prediction and field measurements will be performed. We will first analyze and incorporate measurement data for development of efficient wind forcing and wave breaking dissipation models in direct physical context. The phase-resolved wave simulation will then be used as a powerful vehicle to understand effects of local turbulence processes on large-scale nonlinear wavefield evolution dynamics. Finally, we will evaluate and quantify the validity, efficacy, and limitations of the overall approach, and to develop models and parameterizations to guide practical applications based on this capability.

WORK COMPLETED

Fiscal year of 2007 is the planning year for this five-year High Resolution Air-Sea Interaction DRI. The major work includes:

- Attending two planning meetings in SIO in March and June, respectively; interacting with other investigators; contributing to the science plan.

- Further development of numerical capabilities for the interaction of ocean and wind turbulence with dynamically-evolving surface waves.

- Initial investigation of pressure variation in wind-wave field for the modeling of wind input to wavefield.

- Initial investigation of multiscale modeling and data assimilation.

RESULTS

The main task in this fiscal year is the planning of the DRI. We attended the two planning meetings at SIO in March and June, respectively. We interacted with other investigators, participated in the planning of field measurements in the coming years, and contributed to the science plan.

Besides the planning activities, substantial study on the modeling for high-resolution phase-resolved wave simulation has been performed. One important question is how the pressure varies in wind-wave interactions. Such information is essential for the deployment of pressure sensors in the DRI. It also plays an important role in the study of effects of wind input on the deterministic prediction of wave

propagation. In connection with the PI's YIP project, we investigated pressure statistics in wind-wave interactions.

Figure 1 shows the phase-averaged wave-correlated pressure contours of winds over waves with wave age $c/u_* = 2$ and 14. It is found that, for the young wave with wave age $c/u_* = 2$, the pressure contours are tilted at a short distance above the wave. For the intermediate wave with $c/u_* = 14$, the high pressure region does not extend vertically much comparing to the wave crest. In the presence of a wind-generated surface drift, the low pressure region is shifted towards the trough, while the high pressure region is extended slightly towards the downstream direction. The effect of surface drift on the pressure field for the intermediate wave is less obvious. From the above observation, it is clear that the pressure field information may vary significantly in the vertical direction near the water surface, which indicates the importance of obtaining correct pressure data near the water surface.

While Figure 1 considers the averaged effect of wind input to waves, it is also important to consider the fluctuation of the wind pressure. Such gust effect may be essential for the investigation of wave deterministic prediction, and it is likely that our wind input model will have a stochastic component in addition to the phase-resolved mean wind input. For this purpose, we investigated the probability density distribution of the pressure. Figure 2 shows that the young wave has a wider pressure distribution, i.e. more variation, than the mature wave. It is also found that the young wave is affected substantially by the wind-induced surface drift. Figure 3 shows that in the presence of a wind drift, there exists a significant downstream phase drift, which needs to be captured in the phase-resolved wave prediction for growing sea. Figure 4 compares the histograms of pressure distribution at two different heights above the wave. It is shown that at the leeside and at the trough, the pressure obtained at some distance above has more fluctuations than the true wind input at the wave surface. Such effects should be taken into account in the deployment of pressure measurement sensors and in the analysis of wind input data.

An important issue in this DRI is the multiscale modeling and data assimilation for various measurement and modeling components that are at different scales. It is essential for the SNOW simulation to have wind input over the entire prediction domain at a resolution that matches the simulation. In the fiscal year of 2007, we studied a promising multiscale modeling and data assimilation approach. Our method builds on physics-based upscaling, which links the small-scale physics to parameterization at large scale (a typical example is the extraction of surface roughness for large-scale atmospheric modeling from phase-resolved wave simulation), and on downscaling, which interpolates small-scale phenomena from large-scale data (e.g. from COAMPS or remote sensing data). The downscaling and upscaling modeling are dynamically connected by a successive multiscale simulation approach we developed. While Figures 1 to 4 are for small-scale simulations, large-scale simulation is illustrated in the example shown in Figure 5. In Figure 5, the interaction of the winds with a JONSWAP wavefield is simulated. The coherent wave-induced structures in the atmosphere as well as small-scale fluctuations are clearly seen. This multiscale modeling approach, together with the advanced data assimilation techniques using observability with model variability and subdomain observability, is among the topics of our ongoing research. We hope they will enable us to integrate direct and remote ocean sensing such as radar and lidar into reliable reconstruction and prediction of the phase-resolved wavefield.

IMPACT/APPLICATION

This project is part of an overall coordinated effort involving experimentalists and modelers aiming at basic scientific understanding of the air-sea-wave interaction physics and numerical prediction capability development.   Developments in this project would lead to improved predictions of the phase-resolved surface wavefield around surface vessels and contribute to the safety and effectiveness of naval operations and sea keeping in moderate to high winds and sea states.

RELATED PROJECTS

This work is part of the ONR High Resolution Air-Sea Interaction DRI.
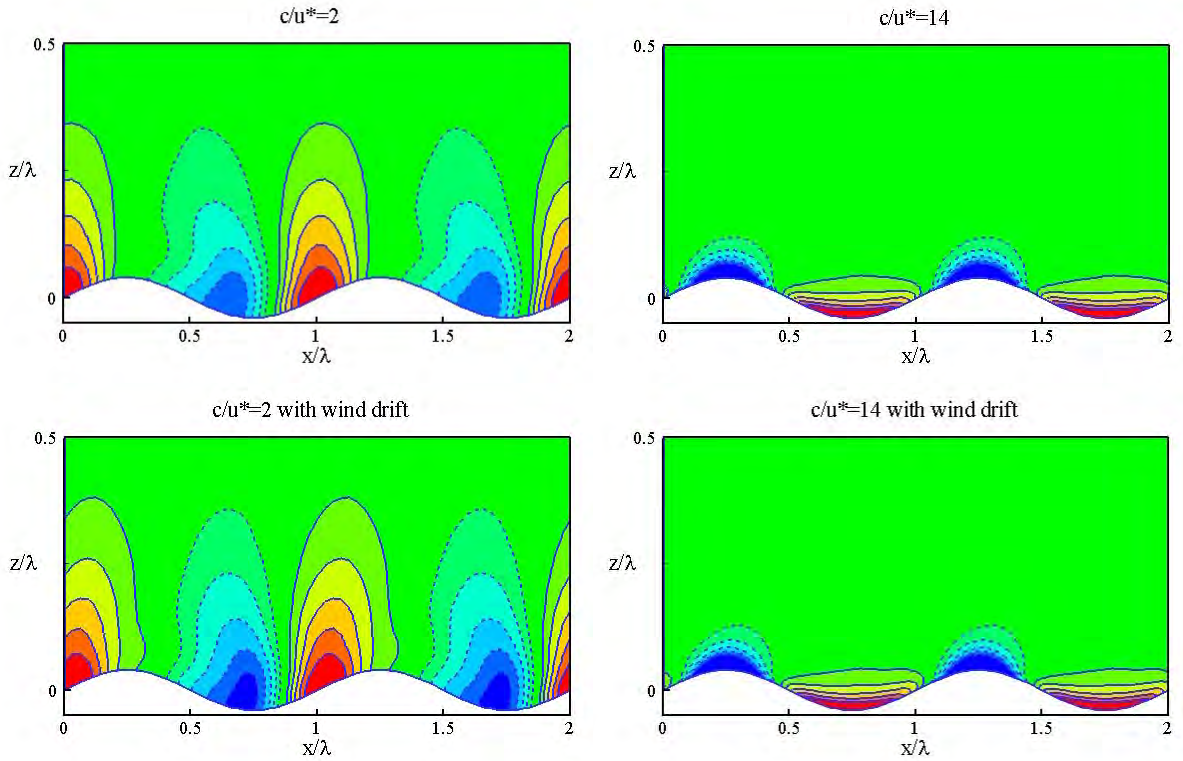
Figure 1. Phase-averaged wave-correlated pressure contours for surface waves with wave age $c/u_* =$ 2 and 14, respectively.   In the two lower figures, the wind-generated surface drift is considered.
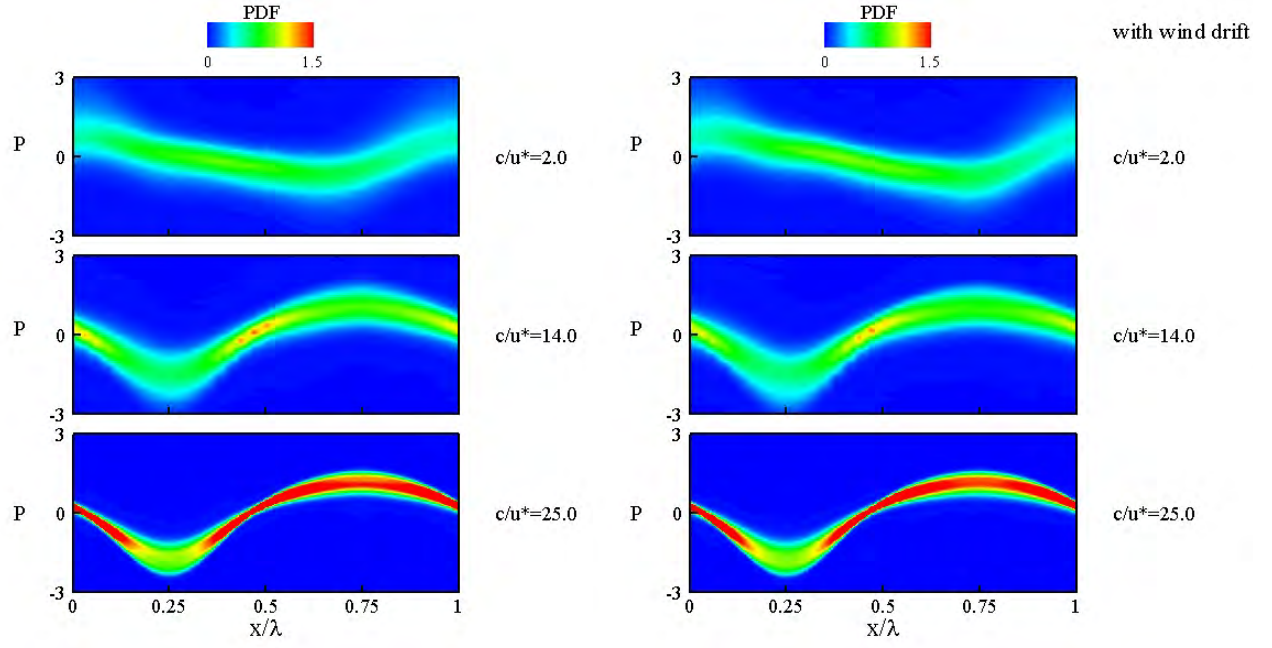
Figure 2.   Probability density function of pressure on the surface of water waves for wave ages of $c/u_* =$ 2, 14, and 25. Here, the wind-generated surface drift is considered in the three figures on the right. The pressure value is normalized by the root-mean-square of the surface pressure fluctuation.
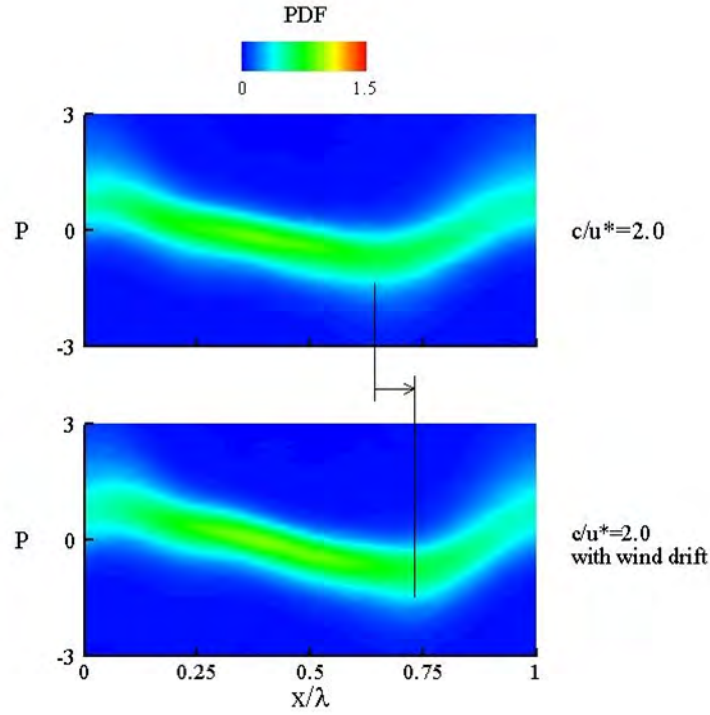

Figure 3. Phase shift effect caused by wind-generated surface drift.
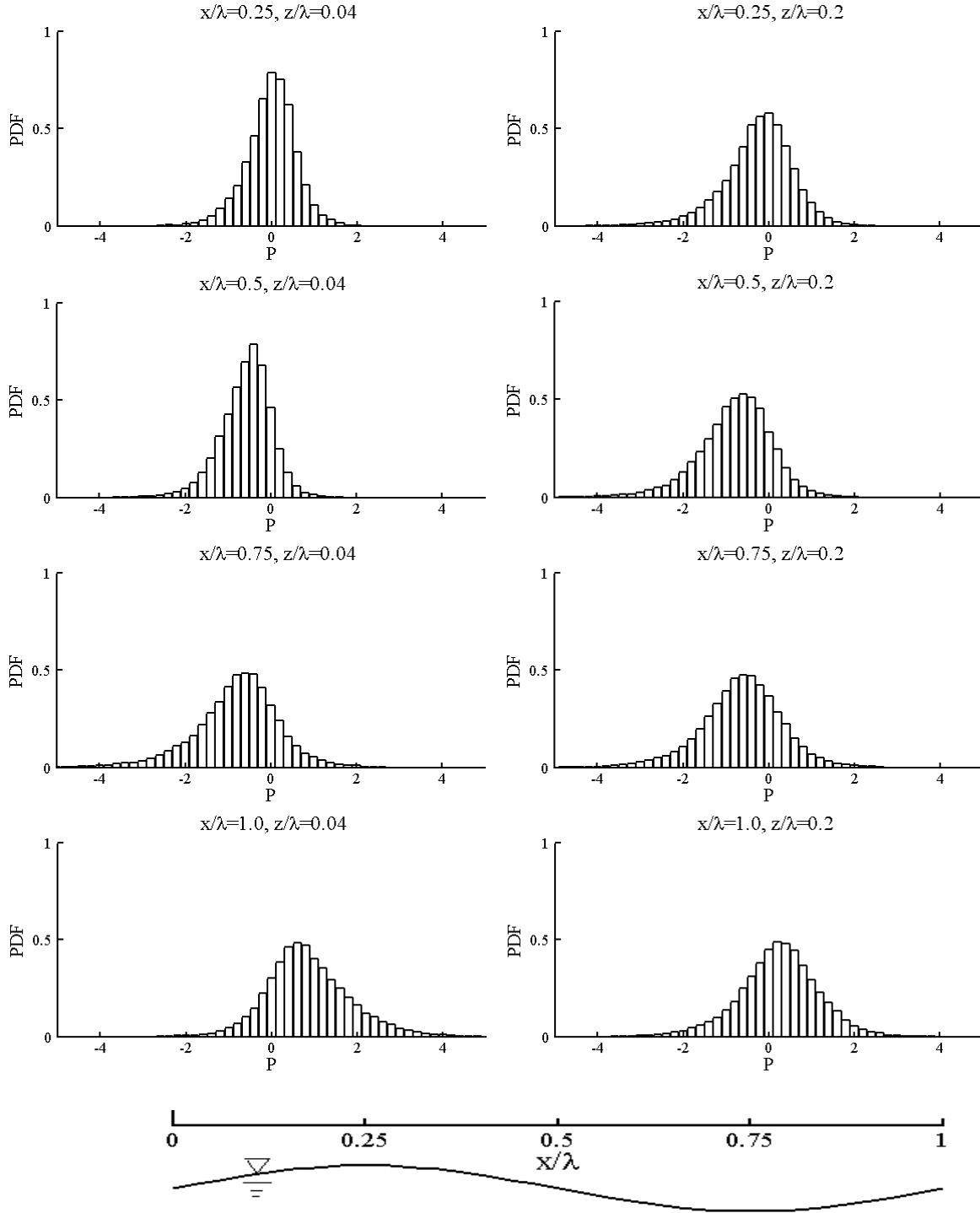
Figure 4. Histograms of pressure distribution probability at different locations for wind over water wave. Wave age is $c/u_* = 2$***. Here, the pressure is normalized by the root-mean-square of the surface pressure fluctuation.***
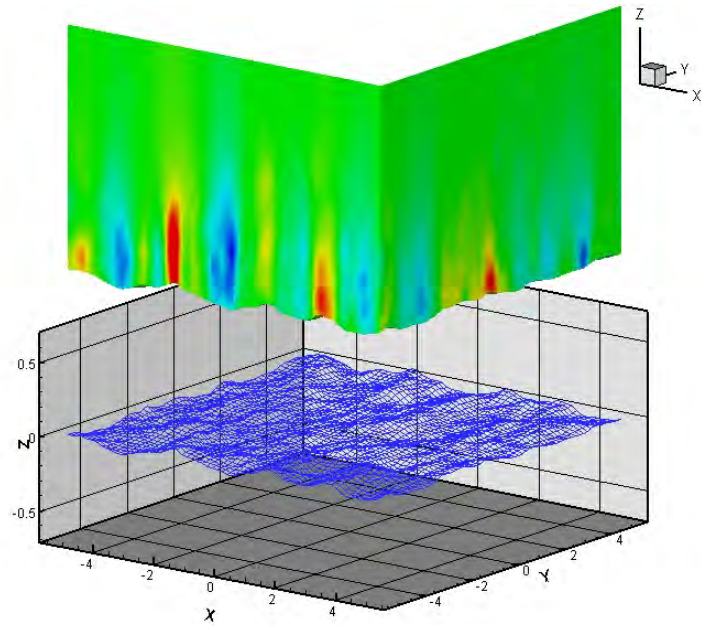
***Figure 5. Illustration of pressure distribution in the wind field over water waves at large scales.
The wavefield is obtained from HOS wave simulation of a JONSWAP spectrum.***